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Published in:
PLOS one

DOI:
[10.1371/journal.pone.0080600](https://doi.org/10.1371/journal.pone.0080600)

Publication date:
2013

Document version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Thorlacius-Ussing, L., Ludvigsen, M., Kirkeby, S., Vorum, H., & Honoré, B. (2013). Proteomic analysis of tissue from 1,3-galactosyltransferase knockout mice reveals that a wide variety of proteins and protein fragments change expression level. *PLOS one*, 8(11), 1-10. [e80600]. <https://doi.org/10.1371/journal.pone.0080600>

Proteomic Analysis of Tissue from α 1,3-galactosyltransferase Knockout Mice Reveals That a Wide Variety of Proteins and Protein Fragments Change Expression Level

Louise Thorlacius-Ussing¹, Maja Ludvigsen², Svend Kirkeby³, Henrik Vorum¹✉, Bent Honoré^{2*}✉

1 Department of Ophthalmology, Aalborg University Hospital, Aalborg, Denmark, **2** Department of Biomedicine, Aarhus University, Aarhus, Denmark, **3** Institute of Odontology, University of Copenhagen, Copenhagen, Denmark

Abstract

A barrier in a pig-to-man xenotransplantation is that the Gal α 1-3Gal β 1-4GlcNAc-R carbohydrate (α -Gal epitope) expressed on pig endothelial cells reacts with naturally occurring antibodies in the recipient's blood leading to rejection. Deletion of the α 1,3-galactosyltransferase gene prevents the synthesis of the α -Gal epitope. Therefore, knockout models of the α 1,3-galactosyltransferase gene are widely used to study xenotransplantation. We have performed proteomic studies on liver and pancreas tissues from wild type and α 1,3-galactosyltransferase gene knockout mice. The tissues were analyzed by two-dimensional polyacrylamide gel electrophoresis and liquid chromatography - tandem mass spectrometry. The analyses revealed that a wide variety of proteins and protein fragments are differentially expressed suggesting that knockout of the α 1,3-galactosyltransferase gene affects the expression of several other genes.

Citation: Thorlacius-Ussing L, Ludvigsen M, Kirkeby S, Vorum H, Honoré B (2013) Proteomic Analysis of Tissue from α 1,3-galactosyltransferase Knockout Mice Reveals That a Wide Variety of Proteins and Protein Fragments Change Expression Level. PLoS ONE 8(11): e80600. doi:10.1371/journal.pone.0080600

Editor: Valquiria Bueno, UNIFESP Federal University of São Paulo, Brazil

Received: July 3, 2013; **Accepted:** October 4, 2013; **Published:** November 14, 2013

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Funding: The work was supported by the Bagger-Sørensen Foundation, the John and Birthe Meyer Foundation and the MEMBRANES Center at Aarhus University. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors have declared that no competing interests exist.

* E-mail: bh@biokemi.au.dk

✉ These authors contributed equally to this work.

Introduction

The first barrier in a pig-to-man xenotransplantation is that the Gal α 1-3Gal β 1-4GlcNAc-R carbohydrate (α -Gal epitope) expressed on pig endothelial cells will react with naturally occurring xenoreactive circulating antibodies in the recipient's blood leading to hyperacute rejection of the discordant xenograft within a few minutes. Deletion of the α 1,3-galactosyltransferase gene will prevent synthesis of the α -Gal epitope and generation of α -Gal transferase knockout animals is therefore an important step for xenotransplantation of vascularised organs [1]. The results from grafting α -Gal transferase knockout organs into non-human primates show that many biological barriers such as human antibodies against pig antigens must be overcome before being a clinical reality [2]. Thus, carbohydrate antigens other than the Gal antigen (i.e. non-Gal antigens) such as blood group AO and related antigens, Tn and Sialyl-Tn antigens and perhaps other saccharides to which humans have preformed antibodies may

cause pig xeno-rejection [3,4]. Further, knockout of a gene may eliminate the construction of its specific gene product, but it may also influence the expression of other proteins that may be up- or downregulated [5,6]. The α -Gal epitope is expressed in wild type mice and therefore the α 1,3-galactosyltransferase knockout models have been extensively used in xenotransplantation studies. To determine if other proteins are differentially expressed in α 1,3-galactosyltransferase knockout mice compared to wild type mice, we performed proteomic analyses of liver and pancreas tissues by using two dimensional polyacrylamide gel electrophoresis (2D-PAGE) and liquid chromatography - tandem mass spectrometry (LC-MS/MS) to identify such protein candidates.

Materials and Methods

C57BL/6 mice, 3-months-old, all male were included in the study. All procedures were conducted under protocols approved by the Danish Animal Care and Ethics Committee

and conducted in accordance with the Danish Animal Experimentation Act and European Convention for the protection of vertebrate animals used for experimental and other scientific purposes. Half of the mice were α -Gal knockout mice, lacking a functional α 1,3-galactosyltransferase gene, C57BL/6/CimIKvl-Tgaltm1Tea. The mice were generated as described by Tearle et al. [7] hereafter termed KO mice. The phenotype was confirmed by development of cataracts at 4–6 weeks of age and by PCR. C57BL/6JBomTac mice, hereafter termed wt mice, were used as controls. The mice had free access to food and water and were sacrificed between 10 a.m. and noon. Specimens from the liver and pancreas were frozen in isopentane cooled to -150°C with liquid nitrogen. Some samples were cut on a cryostat in 6μ sections for histochemistry while other were processed for electrophoresis. The lectin to detect the α -Gal epitope in tissue sections was a biotinylated *Griffonia simplicifolia* isolectin (GS1-B4; EY Laboratories, San Mateo, CA, USA). The sections were incubated for 24 h at 4°C with $5\mu\text{g/ml}$ of the lectin, diluted 1:200 from a stock solution of 1 mg/ml in TBS. The incubation medium contained 20 mM CaCl_2 and MgCl_2 . After a $3\times 5\text{ min}$ rinse in TBS the sections were immersed in Alexa Fluor 488 streptavidin conjugate for 30 min. The sections were mounted with a fluorescence mounting medium with the DNA binding agent 4'-6-diamidino-2-phenylindole (DAPI; Vector Lab, Burlingame CA, USA).

Two-dimensional gel electrophoresis (2D-PAGE)

Liver and pancreas tissue samples were taken from three wt and three KO mice. Tissue samples were dissolved in lysis buffer consisting of 9 M urea, 2% DTT, 2% Triton X-100 and 2% IPG buffer. Horizontal isoelectric focusing was performed using a non-linear pH3-10NL IPG strip, rehydrated for 20 hours at room temperature with a rehydration buffer (8 M urea, 2% CHAPS, 2% IPG-buffer, 0.3% DDT). The first dimension was carried out on a Multiphor II Electrophoresis unit at 500 V for 5 hours and at 3500 V for 14.5 hours. Prior to the second dimension, the IPG strip was equilibrated twice with an equilibration buffer (0.05 M Tris-base, 6 M Urea, 26% glycerol, 1% SDS), and transferred to a polyacrylamide gel. The second dimension separation was run vertically at 50 V for 19 hours [8]. One gel was performed for each tissue sample from one mouse, thus three biological replicates were analysed for each tissue.

Silver staining

Visualisation was achieved by silver staining, suitable for quantitative protein analysis [8,9]. Briefly, gels were fixed overnight in a fixation solution (50% ethanol, 12% acetic acid and 0.0185% formaldehyde), then washed three times for 20 minutes in 35% ethanol, pre-treated for one min in 0.02% $\text{Na}_2\text{S}_2\text{O}_3$, and rinsed in water 3 times for 2–3 min. Staining of gels with silver nitrate was performed for 20 minutes, after which they again were rinsed twice with water. Gels were developed using a developer solution (6% Na_2CO_3 , 0.0185% formaldehyde, 0.0004% $\text{Na}_2\text{S}_2\text{O}_3$, $5\text{ H}_2\text{O}$) for approximately 3 min. Development was finally stopped in a stop solution (40% ethanol, 12% acetic acid). The gels were dried in cellophane sheets and sealed in plastic bags.

Image analysis

Silver stained gels were scanned using an ImageQuant LAS-4000 (GE Healthcare) and TIFF images of gels were imported into the PDQuest software analysis program. Two proteomic analyses were done; one with pancreatic tissue and one with hepatic tissue. The 2D-gels were divided in two groups; one representing wt mice and another representing KO mice. Protein spots were automatically defined and adjusted to the background. The quality of each protein spot was critically evaluated in order to ensure that all relevant protein spots were identified. The pixel-intensity of each protein spot was translated to a proportional protein volume, which was normalized to the total density of the gel and given in parts per million, ppm. Finally, re-analysis was done manually on all matched spots. Differentially expressed spots were defined as spots that differed at least 2-fold in average relative volume between the groups of wt and KO mice. The results were considered to be significant when $p < 0.05$ using a student's t-test. These spots were selected for further identification by LC-MS/MS.

Protein identification

Protein identification by LC-MS/MS was performed essentially as previously described [8]. Briefly, gels containing protein spots selected for identification were re-hydrated in water, the cellophane sheets were peeled off and the protein spots were excised from the gels. Proteins were *in-gel* digested with trypsin. Gel pieces were first dehydrated in acetonitrile, then dried and the proteins reduced for 1 h at 56°C in 10 mM dithiothreitol (DTT) and 100 mM NH_4HCO_3 . The solution was exchanged with 55 mM iodoacetamide in 100 mM NH_4HCO_3 for 45 min. Then the gel pieces were washed in 100 mM NH_4HCO_3 , dehydrated in acetonitrile, rehydrated in 100 mM NH_4HCO_3 , dehydrated in acetonitrile, dried and swelled in digestion buffer (50 mM NH_4HCO_3 , 5 mM CaCl_2 and $12.5\text{ ng}/\mu\text{l}$ trypsin Gold (mass spectrometry grade; Promega, Madison, WI, USA). Digestion was performed overnight at 37°C and the peptides were extracted by 1 change of 20 mM NH_4HCO_3 and 3 changes of 5% formic acid in 50% acetonitrile. The samples were finally dried and the peptides resuspended in $6\mu\text{l}$ of buffer A (water/acetonitrile/formic acid, $97.7/2/0.3$, V/V/V). The peptides were separated using an inert nano LC system composed of a Famos micro autosampler, a Switchos micro column switching module and an Ultimate micro pump from LC Packings (San Francisco, CA) before MS analysis. Of the *in-gel* digested samples $5\mu\text{l}$ was preconcentrated and desalted on a $300\mu\text{m}$ inner diameter \times 5 mm nano-precolumn (LC Packings) packed with $5\mu\text{m}$ C18 PepMap100 material. A $75\mu\text{m}$ inner diameter \times 15 cm nano-column packed with $3\mu\text{m}$ C18 PepMap100 material was used to separate the peptides. Elution from the column was made with a gradient by mixing decreasing volumes of buffer A with increasing volumes of buffer B (water/acetonitrile/formic acid, $9.7/90/0.3$, V/V/V). The peptides were eluted into the nano electrospray ion source of the quadrupole time-of-flight (Q-TOF) Premier mass spectrometer (Waters). MS survey scans were acquired using MassLynx 4 SP4 (Waters) from m/z values between 450–1500. The instrument was operated in a data-dependent MS to

MS/MS switching mode. Doubly, triply and quadruply charged peptide ions detected in MS survey scans triggered a switch to MS/MS for obtaining peptide fragmentation spectra with an interval of m/z values between 50–1800. [Glu¹]-fibrinopeptide B (GFP), 300 fmol/ μ l, was used as lock mass injected at a flow rate of 300 nl/min. GFP was also used to calibrate the TOF unit. Raw data were processed using ProteinLynx GlobalServer 2.1 (Waters) with processing parameters: Background Subtract: Normal, Background Threshold: 35%, Background Polynomial: 5, Smoothing Type: Savitzky-Golay, Smoothing Iterations: 2, Smoothing Window: 2 channels, Deisotoping Type: Normal, Deisotoping Threshold: 1%. The processed data were used to search the mouse fraction of the Swiss-Prot database (release 2011_11 or 2013_05) using the on-line version of the Mascot MS/MS Ion Search facility (Matrix Science, Ltd., <http://www.matrixscience.com>) [10]. Searching was performed with doubly, triply and quadruply charged ions with up to 2 missed cleavages, a peptide tolerance of 20 ppm, one variable modification, Carbamidomethyl-C, and an MS/MS tolerance of 0.05 Da. Spectra of dubious identifications were evaluated manually and omitted if they were of insufficient quality. Contaminating peptides and cross-contaminating peptides from previous samples including keratins, trypsin, BSA and casein were disregarded. At least one 'bold red' peptide with scores giving a less than 5% probability that the observed match was a random event was required in the search for protein hits. All peptides for these hits are reported. If the first search in the mouse fraction of the Swiss-Prot database did not give any hit an additional search in the whole database was performed.

Results

The staining pattern of the tissues used for the present analysis is shown in Figure 1. As expected GS1B4 stains the endothelial cells in the central vein as well as in the sinusoids of the wt liver whereas the α 1,3-galactosyltransferase KO liver is unstained. In the pancreas the endothelial cells are unstained while the exocrine cells are stained in the mouse wt pancreas as well as in the KO pancreas. Figure 2 shows representative 2D-gels of wt and KO tissues from mouse liver and pancreas, respectively. Spots whose expression differed by at least 2-fold between the wt and the KO tissues are highlighted.

Liver

In total 22 spots were found to be differentially expressed in α 1,3-galactosyltransferase gene KO mice relative to wt mice as shown in Figure 2 panel A. Eight spots were upregulated, marked with green numbers, and 14 spots were downregulated, illustrated by red numbers. All spots were excised and subjected to mass spectrometry identification as summarised in Table 1. Eighteen spots were successfully identified. Of these, 12 were found to contain one protein that accounts for the observed change in expression. Six spots contained more than one protein (Nos. 0511, 2514, 3113, 6207, 6311 and 7104) in which case, we cannot with certainty conclude which of them accounts for the observed change in

expression level. Interestingly, in the vast majority of cases we observed a major deviation of the observed molecular mass by 2D-PAGE with the theoretical molecular mass of the proteins, as illustrated in Figure 3. α -tubulin has a molecular mass around 50 kDa but spot 2514 migrated with a molecular mass below 40 kDa (Figure 3A). A map of the identified peptides showed that spot 2514 contained an N-terminal fragment of tubulin. A change in the concentration of a protein fragment may occur as a result of a change in the synthesis as well as a change in the degradation as it is the case with a full-length protein. Thus, it seems that for some proteins there is a substantial change in protein turnover in the KO liver.

Identified upregulated protein spots included adenosylhomocysteinase fragment (2001), serum albumin (3812), 2-hydroxyacyl-CoA lyase 1 (5813) and isocitrate dehydrogenase [NADP] cytoplasmic fragment (6414). Downregulated spots included heat shock cognate 70 kDa protein 3 fragment (0413), glutathione S-transferase P 1 (2203), betaine-homocysteine S methyltransferase 1 fragment (3209), aldehyde dehydrogenase fragment (3210), myosin-9 fragment (4206), electron transfer flavoprotein subunit α fragment (6102), arginase-1 fragment (7202) and urocanate hydratase (8803). Only one protein of all identified proteins in Table 1 contained a putative N-glycosylation site, namely carboxylesterase 3 (spot 6207).

Pancreas

In total 39 differentially expressed spots were detected by 2D-PAGE analysis (Figure 2, panel B). All spots were excised and resulted in identification of 17 spots as summarised in Table 2. All of these were found to contain a single identification and about a third of them contained fragments of the proteins. Thus, there is also a substantial change in protein turnover for some proteins in the KO pancreas tissue. Of upregulated proteins, the following eight were identified; albumin fragment (2602), tensin-3 fragment (7702), serotransferrin (7808), chymotrypsin-like elastase family member 1 (8305), NADH dehydrogenase [ubiquinone] flavoprotein 1 (8604), ATP synthase subunit α , mitochondrial (8615), aconitate hydratase, mitochondrial (8802) and 3-hydroxyacyl-CoA dehydrogenase type 2 (9303). Identified downregulated proteins were 78 kDa-glucose-regulated protein (1811), apolipoprotein A-1 (2315), glutathione S-transferase P1 (3215), 40S ribosomal protein S12 (5005), proteasome subunit β type-3 (5208), serum albumin fragment (5413), myeloperoxidase fragment (5415), GTP-binding protein SAR1a (6202) and serum albumin fragment (6304). Of all identified proteins in Table 2, only four contained putative N-glycosylation sites, i.e., myeloperoxidase, serotransferrin, receptor-type tyrosine-protein phosphatase α and chymotrypsin-like elastase family member 1.

Discussion

The α -Gal epitope may be stronger expressed in some organs than in other. As an example incubation with the α -galactose specific lectin GS1B4 stains the endothelial cells in the liver from wt mice [7] while there is no lectin reaction in the

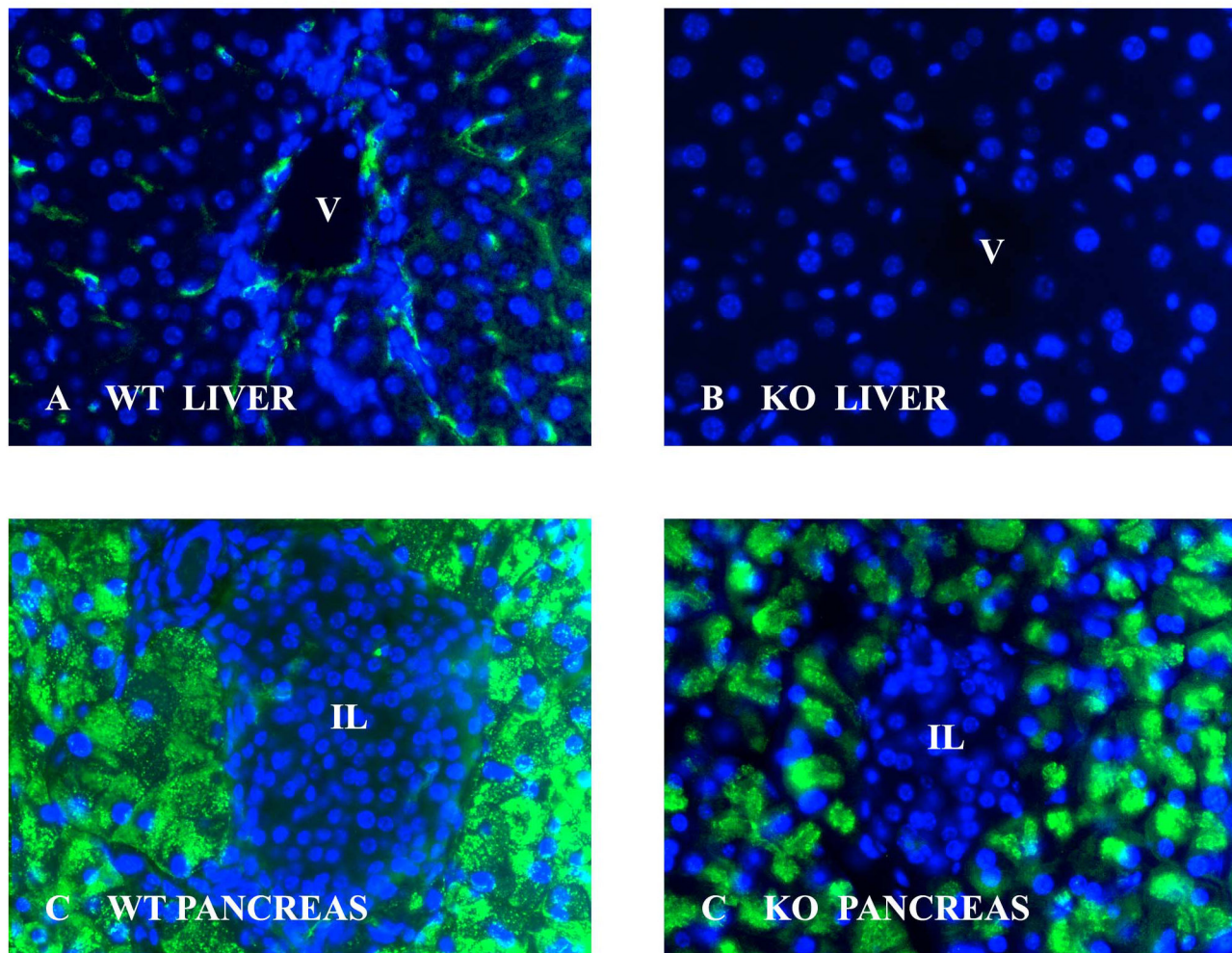


Figure 1. GS1B4 staining of wt and α 1,3-galactosyltransferase KO mouse tissues. The lectin stains the central vein (v) and the sinusoids are outlined in sections from the wt mouse liver (A) while there is no reaction in sections from the KO mouse liver (B). There is no staining of the blood vessels in pancreas from neither the wt mouse (C) nor from the KO mouse (D). The endocrine cells in islets of Langerhans (IL) are unstained while the exocrine cells in both the wt and the KO mouse show reaction. The green fluorescence reflects lectin staining and blue fluorescence reflects DAPI staining of the nuclei.

doi: 10.1371/journal.pone.0080600.g001

endothelial cells in the wt mouse pancreas [11]. It also seems that heterozygote GalT-KO pigs display a significantly lower activity for α 1,3-galactosyltransferase in some organs than in other [12]. In the present analysis, we confirmed presence of the α -Gal epitope on the endothelial cells of the wt liver as well as the absence on the endothelial cells in the pancreas (Figure 1). Liver cells do not stain in wt as well as in KO mice while cells of the exocrine pancreas are stained in wt as well as in KO mice.

Although hyperacute rejection can be prevented in transplantation with organs from α 1,3-galactosyltransferase KO, the grafts are lost after some months with signs of thrombotic microangiopathy. This could be due to the action of non-Gal antibodies that aim at proteins or carbohydrates in the transplanted organs from the GalT-KO animal [13]. The

presence of non-xenoreactive antigens might also explain why GS1 B4 stains the exocrine pancreatic cells of both mouse strains. GS1 B4 is widely used as a probe for α -D-Galactosyl end groups. It has thus been shown that the isolectin detects not only the xenoreactive Gal α 1-3Gal β 1-4GlcNAc carbohydrate but also the P blood group antigens P^k: Gal α 1-4Gal β 1-4Glc β - and P_i: Gal α 1-4Gal β 1-4GlcNAc β [14] and galabiose (Gal α 1-4Gal) which is an epithelial surface cell receptor for Shiga like toxins. GS1 B4 also exhibits broad specificity for blood group B variants and can react with type 1 [Gal α 1-3(Fuc α 1-2)Gal β 1-3GlcNAc], type 2 [Gal α 1-3(Fuc α 1-2)Gal β 1-4GlcNAc] and their difucosylated variants [15]. Although the xenoreactive α -Gal epitope seems to be a blood group B epitope that lacks the fucose residue it is important to realize that the two determinants are

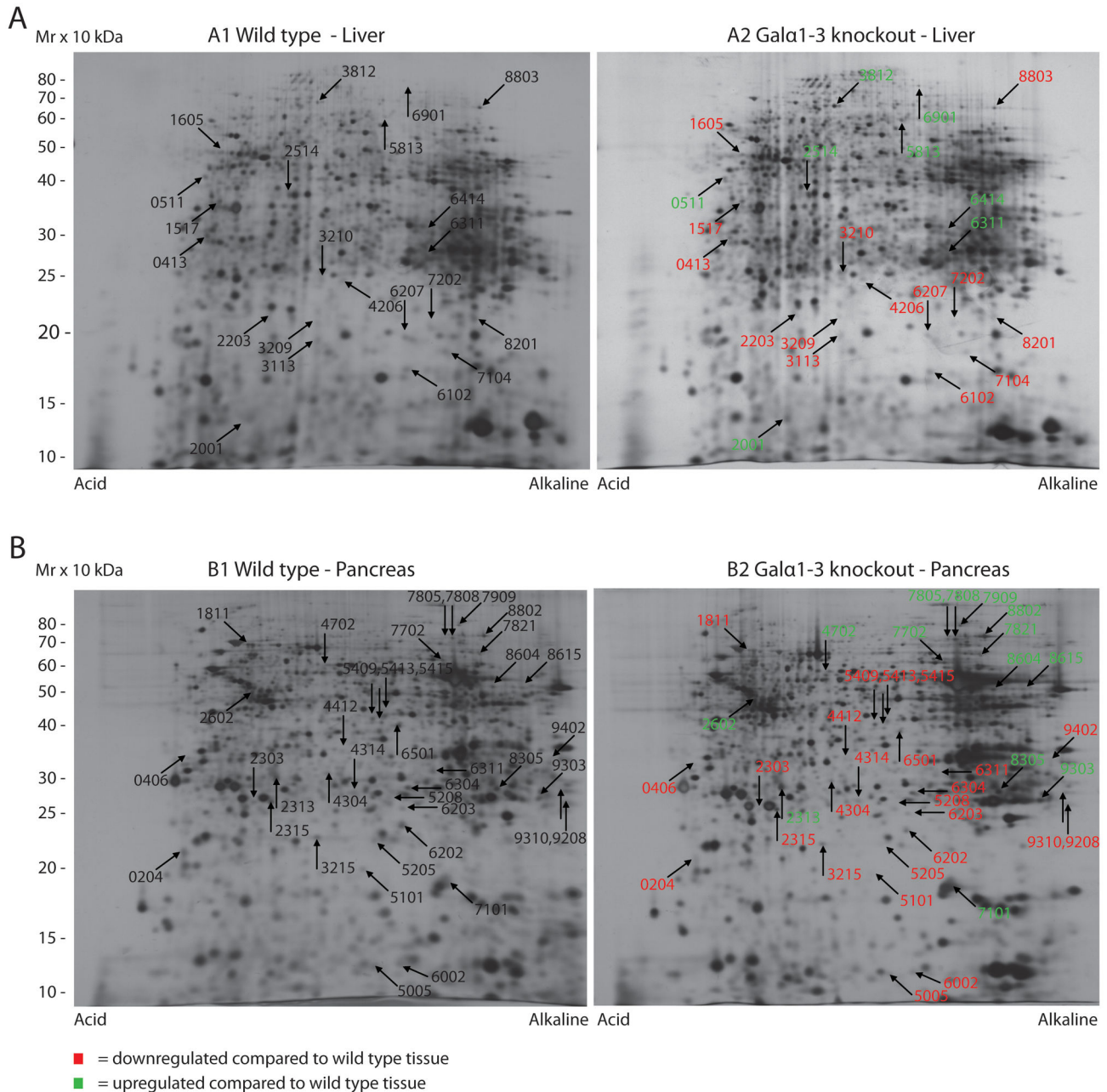


Figure 2. 2D-PAGE images of wt and α 1.3-galactosyltransferase KO mouse tissues. Liver (A) and pancreas (B). Proteins which are at least 2-fold differentially expressed are marked with red (downregulated) and green (upregulated). Identified proteins are listed in Tables 1 and 2.

doi: 10.1371/journal.pone.0080600.g002

biosynthesized by two distinct α 1,3galactosyltransferases and are thus genetically unrelated [16]. It is therefore a possibility that the staining of exocrine cells in both strains reflects the presence of a glycan with a α -D-Galactosyl end group other than the xenoreactive carbohydrate.

In non-primate mammals anti-Gal antibodies may bind, not only to endothelial cells but also to epithelial cells,

mesenchymal cells and extracellular matrix glycoproteins [17]. Terminal Gal α 1-3Gal is thus present in both glycoprotein- and glycolipid bound forms [18] and Everett et al. [19] measured that on endothelial cells 13 percent of Gal α 1-3Gal are present on glycolipid and 87 percent on glycoprotein. In future modifications of immunosuppressive therapy and strategies to induce tolerance, it would be important to reveal if targeted

Table 1. Differentially expressed protein spots in mouse α 1,3-galactosyltransferase KO liver.

| Spot | Ratio (KO/wt) | wt, Vol. \pm SD (ppm) | KO, Vol. \pm SD (ppm) | Peptides | Identification | Mr (Da) | Mascot Protein Score | Protein name |
|------|------------------|----------------------------|----------------------------|-------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------|--------------------------------------------|----------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 0413 | 0.31 | 745 \pm 251 | 229 \pm 98 | FELTGIPPAPR SINPDEAVAYGAAVQAAILSGDK | HSP7C_MOUSE | 70827 | 112 | Heat shock cognate 70 kDa protein 3, fragment |
| 0511 | 3.31 | 55 \pm 20 | 181 \pm 48 | ITITNDQNR VYEGERPLTK / VLVGANFEEVAFDEK | GRP78_MOUSE / PDIA1_MOUSE | 72377 / 57023 | 33 29 | 78 kDa glucose-regulated protein, fragment Protein disulfide-isomerase, fragment |
| 1517 | 0.47 | 648 \pm 164 | 307 \pm 75 | N.I.* | | | | |
| 1605 | 0.36 | 479 \pm 79 | 171 \pm 165 | N.I. | | | | |
| 2001 | 2.35 | 866 \pm 232 | 2035 \pm 482 | ALDIAENEMPLMR | SAHH_MOUSE / | 47657 | 42 | Adenosylhomocysteinase, fragment |
| 2203 | 0.20 | 765 \pm 212 | 151 \pm 177 | PPYTIVYFPVR FEDGDLTYQSNAIR | GSTP1_MOUSE | 23594 | 81 | Glutathione S-transferase P 1 |
| 2514 | 2.73 | 344 \pm 56 | 937 \pm 365 | QLFHPEQLITGK AVFVDLEPTVIDEVR NLDIERPTYTNLNR IHFLPATYAPVISAEEK TIGGGDDSFNTFFSETGAGK / KYEATLEK LGEYGFQNAILVR | TBA1A_MOUSE or TBA1B_MOUSE or TBA1C_MOUSE / ALBU_MOUSE | 50104 / 68648 | 269 30 | Tubulin α -1A/1B/1C chain, fragment Serum albumin, fragment |
| 3113 | 0.31 | 1526 \pm 441 | 471 \pm 228 | TAHIVLEDGK / EKVDLLFLGK GIHVEIPGAQAESLGPLQVAR | CPSM_MOUSE/ ETFB_MOUSE | 164514 27606 | 50 24 | Carbamoyl-phosphate synthase [ammonia], mitochondrial, fragment Electron transfer flavoprotein subunit β , fragment |
| 3209 | 0.14 | 704 \pm 198 | 97 \pm 59 | VNEAACDIAR | BHMT1_MOUSE | 44992 | 45 | Betaine--homocysteine S methyltransferase 1, fragment |
| 3210 | 0.26 | 481 \pm 99 | 126 \pm 123 | VAEQTPLTALYVANLIK | ALDH2_MOUSE | 56502 | 32 | Aldehyde dehydrogenase, mitochondrial, fragment |
| 3812 | 2.90 | 196 \pm 90 | 569 \pm 189 | KYEATLEK LSQTFPNADFAEITK | ALBU_MOUSE | 68648 | 65 | Serum albumin |
| 4206 | 0.37 | 594 \pm 118 | 218 \pm 173 | NLPYSEEIVEMYK | MYH9_MOUSE | 226232 | 29 | Myosin-9, fragment |
| 5813 | 2.17 | 204 \pm 48 | 441 \pm 120 | TPEELQHSLR | HACL1_MOUSE | 63619 | 45 | 2-hydroxyacyl-CoA lyase 1 |
| 6102 | 0.31 | 1613 \pm 517 | 500 \pm 285 | LLYDLADQLHAAVGASR | ETFA_MOUSE | 34988 | 118 | Electron transfer flavoprotein subunit α , mitochondrial, fragment |
| 6207 | 0.34 | 910 \pm 258 | 310 \pm 94 | IGASTQAAQR DGASEEETNLSK ISENMIPVVAEK / TIPIDGDFFSYTR | CES3_MOUSE / ALDH2_MOUSE | 61749 56502 | 142 28 | Carboxylesterase 3, fragment Aldehyde dehydrogenase, mitochondrial, fragment |
| 6311 | 6.34 | 390 \pm 494 | 2475 \pm 1042 | TIILYDTNLPDVSAK / LALLSLTTGGTAEMYTK / TAHIVLEDGK / FQEAPEEGR ASIYQSVVINTSK IAVIGAGASGLTCIK / TATPQQAQEVHEK | KHK_MOUSE/ NQO2_MOUSE/ CPSM_MOUSE / FMO5_MOUSE / TPIS_MOUSE | 32730 26231 164514 59962 32171 | 96 63 60 56 29 | Ketohexokinase Ribosylidihydronicotinamide dehydrogenase [quinone] Carbamoyl-phosphate synthase [ammonia], mitochondrial, fragment Dimethylaniline monooxygenase [N oxide-forming] 5, fragment Triosephosphate isomerase |
| 6414 | 4.46 | 244 \pm 68 | 1089 \pm 498 | HAYGDQYR LDNNTLSFFAK | IDHC_MOUSE | 46644 | 43 | Isocitrate dehydrogenase [NADP] cytoplasmic, fragment |

Table 1 (continued).

| Spot | Ratio (KO/wt) | wt, Vol. \pm SD (ppm) | KO, Vol. \pm SD (ppm) | Peptides | Identification | Mr (Da) | Mascot Protein Score | Protein name |
|------|---------------|-------------------------|-------------------------|---------------------------------------------------------|-----------------------------|------------------|----------------------|-----------------------------------------------------------------|
| 6901 | 2.92 | 41 \pm 11 | 119 \pm 34 | N.I. | | | | |
| 7104 | 0.28 | 1343 \pm 337 | 375 \pm 344 | DHGDIAFVDVPNDSSFQIVK / IDPSAPLKD AGDTVIPLIYQCCECK | ARGI1_MOUSE / ADHX_MOUSE | 34786 / 39522 | 71 50 | Arginase-1, fragment Alcohol dehydrogenase class-3, fragment |
| 7202 | 0.13 | 1033 \pm 405 | 132 \pm 121 | VMEETFSYLLGR | ARGI1_MOUSE | 34786 | 66 | Arginase-1, fragment |
| 8201 | 0.26 | 1671 \pm 109 | 431 \pm 378 | N.I. | | | | |
| 8803 | 0.46 | 498 \pm 40 | 228 \pm 150 | VAIAVAINQAIASGK TPNLSPEEEQLALR | HUTU_MOUSE | 74543 | 82 | Urocanate hydratase |

Searches were performed in the Swiss-Prot mouse database.

*. N.I.: not identified.

doi: 10.1371/journal.pone.0080600.t001

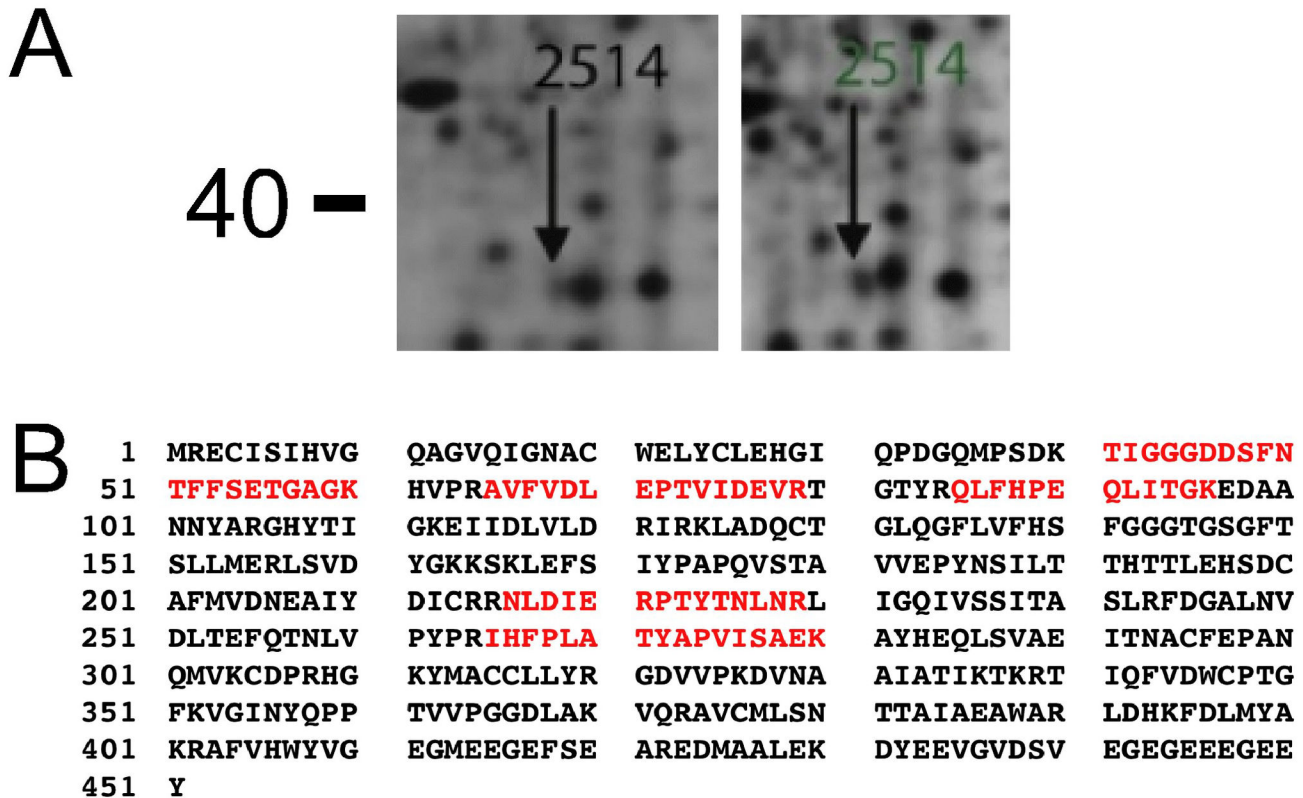


Figure 3. Spot No. 2514 is a fragment of α -tubulin. A) Spot 2514 migrates with a molecular mass below 40 kDa. The identified peptides from the spot are distributed in the N-terminal of α -tubulin and spot 2514 thus corresponds to a fragment of α -tubulin, since α -tubulin possesses a molecular mass around 50 kDa.

doi: 10.1371/journal.pone.0080600.g003

disruption of the α 1,3-galactosyltransferase gene also affects the expression of other proteins in the genetically modified animals. Some evidence for this hypothesis is reported in the literature: The content of sialic acid is altered in the GalT-KO

organs and Park et al. [12] noticed an increase of Neu5Gc content in heart, lung, liver and kidney from heterozygote GalT-KO pigs. Diswall et al. [13] found increased levels of uncapped LacNAc precursor and fucosylated H type 2 determinants in

Table 2. Differentially expressed protein spots in mouse α 1,3-galactosyltransferase KO pancreas.

| Spot | Ratio (KO/ wt) | Vol \pm SD (ppm) | KO, Vol \pm SD (ppm) | Peptides | Identification | Mr (Da) | Mascot Protein Score | Protein name |
|--------|-----------------|--------------------|------------------------|----------------------------|----------------|---------|----------------------|-----------------------------------|
| 0204 | 0.18 | 1527 \pm 41 | 282 \pm 217 | N.I.* | | | | |
| 0406 | 0.28 | 216 \pm 61 | 60 \pm 48 | N.I. | | | | |
| 1811 | 0.15 | 926 \pm 261 | 138 \pm 70 | ITITNDQNR | GRP78_MOUSE | 72377 | 244 | 78 kDa glucose-regulated protein |
| | | | | SDIDEIVLVGGSTR | | | | |
| | | | | TFAPEEISAMVLTK | | | | |
| | | | | ITPSYVAFTPEGER | | | | |
| | | | | IINEPTAAAIAYGLDKR | | | | |
| | | | | SQIFSTASDNQPTVTIK | | | | |
| 2303 | 0.14 | 420 \pm 199 | 59 \pm 67 | N.I. | | | | |
| 2313 | 3.12 | 1032 \pm 198 | 3221 \pm 1189 | N.I. | | | | |
| 2315 | 0.16 | 1030 \pm 353 | 161 \pm 132 | HSLMPMLETLK | APOA1_MOUSE | 30569 | 142 | Apolipoprotein A-I |
| | | | | SNPTLNEYHTR | | | | |
| | | | | VAPLGAELQESAR | | | | |
| | | | | VQPYLDEFQKK | | | | |
| 2602 | 4.88 | 242 \pm 140 | 1182 \pm 504 | LGEYGFQNAILVR | ALBU_MOUSE | 68648 | 55 | Serum albumin, fragment |
| 3215 | 0.33 | 989 \pm 173 | 322 \pm 172 | PPYTIVYFPVR | GSTP1_MOUSE | 23594 | 78 | Glutathione S-transferase P 1 |
| | | | | FEDGDLTLYQSNAILR | | | | |
| 4304 | 0.30 | 619 \pm 156 | 187 \pm 127 | N.I. | | | | |
| 4314 | 0.27 | 695 \pm 194 | 190 \pm 151 | N.I. | | | | |
| 4412 | 0.17 | 350 \pm 159 | 60 \pm 62 | N.I. | | | | |
| 4702 | 3.50 | 126 \pm 67 | 440 \pm 44 | N.I. | | | | |
| 5005** | 0.20 | 1120 \pm 485 | 228 \pm 88 | LVEALCAEHQINLIK | RS12_BOVIN | 14505 | 97 | 40S ribosomal protein S12 |
| 5101 | 0.18 | 493 \pm 168 | 89 \pm 45 | N.I. | | | | |
| 5205 | 0.14 | 531 \pm 80 | 72 \pm 48 | N.I. | | | | |
| 5208 | 0.32 | 791 \pm 277 | 254 \pm 57 | FGPYYTEPVIAGLDPK | PSB3_MOUSE | 22949 | 43 | Proteasome subunit β type-3 |
| 5409 | 0.10 | 742 \pm 293 | 74 \pm 112 | N.I. | | | | |
| 5413 | 0.23 | 448 \pm 103 | 104 \pm 84 | LSQTFPNADFAEITK | ALBU_MOUSE | 68648 | 48 | Serum albumin, fragment |
| 5415 | 0.12 | 1319 \pm 488 | 160 \pm 64 | TITGHCCNNR | PERM_MOUSE | 81130 | 25 | Myeloperoxidase, fragment |
| 6002 | 0.27 | 1336 \pm 400 | 359 \pm 167 | N.I. | | | | |
| 6202** | 0.25 | 1960 \pm 152 | 495 \pm 158 | LVFLGLDNAGK | SAR1A_BOVIN | 22395 | 66 | GTP-binding protein SAR1a |
| | | | | EIFGLYGQTTGK | | | | |
| 6203 | 0.31 | 527 \pm 163 | 164 \pm 20 | N.I. | | | | |
| 6304 | 0.19 | 1797 \pm 817 | 341 \pm 115 | KYEATLEK | ALBU_MOUSE | 68648 | 344 | Serum albumin, fragment |
| | | | | TPVSEHVTK | | | | |
| | | | | CCTLPEDQR | | | | |
| | | | | APQVSTPTLVEAAR | | | | |
| | | | | LGEYGFQNAILVR | | | | |
| | | | | RPCFSALTVDETYVPK | | | | |
| | | | | AADKDTCFSTEGPNLVTR | | | | |
| | | | | CCAEANPPACYGTVLAEFQPLVEEPK | | | | |
| 6311 | 0.25 | 774 \pm 205 | 193 \pm 160 | N.I. | | | | |
| 6501 | 0.18 | 1558 \pm 347 | 273 \pm 185 | N.I. | | | | |
| 7101 | 7.43 | 622 \pm 776 | 4621 \pm 1848 | N.I. | | | | |
| 7702 | 4.88 | 198 \pm 207 | 969 \pm 366 | FPDYGKIELVFSATPEK | TENS3_MOUSE | 155491 | 36 | Tensin-3, fragment |
| 7805 | 3.23 | 109 \pm 45 | 351 \pm 22 | N.I. | | | | |
| 7808 | 3.25 | 181 \pm 185 | 586 \pm 139 | GTDFQLNQLEGK | TRFE_MOUSE | 76674 | 55 | Serotransferrin |
| | | | | LYLGHNHYVTAIR | | | | |
| 7821 | 3.15 | 227 \pm 32 | 717 \pm 131 | N.I. | | | | |

Table 2 (continued).

| Spot | Ratio (KO/ wt) | Vol \pm SD (ppm) | KO, Vol \pm SD (ppm) | Peptides | Identification | Mr (Da) | Mascot Protein Score | Protein name |
|------|-----------------|--------------------|------------------------|---------------------|----------------|---------|----------------------|---------------------------------------------------------------|
| 7909 | 5.37 | 73 \pm 92 | 389 \pm 89 | N.I. | | | | |
| 8305 | 4.86 | 474 \pm 578 | 2307 \pm 238 | NNVVAGYDIALLR | CELA1_MOUSE | 28882 | 52 | Chymotrypsin-like elastase family member 1 |
| 8604 | 3.11 | 227 \pm 142 | 707 \pm 130 | GEFYNEASNQLQVAIR | NDUV1_MOUSE | 50802 | 138 | NADH dehydrogenase [ubiquinone] flavoprotein 1, mitochondrial |
| | | | | NACGSDYDFDVFVVR | | | | |
| 8615 | 3.55 | 178 \pm 151 | 631 \pm 181 | HALIYDDLSK | ATPA_MOUSE | 59716 | 28 | ATP synthase subunit α , mitochondria |
| 8802 | 6.74 | 334 \pm 138 | 2252 \pm 282 | NAVTFEFGPVPDTR | ACON_MOUSE | 85410 | 82 | Aconitate hydratase, mitochondrial |
| 9208 | 0.12 | 1380 \pm 431 | 159 \pm 200 | N.I. | | | | |
| 9303 | 4.78 | 416 \pm 340 | 1991 \pm 219 | VVTIAPGLFATPLTTLPEK | HCD2_MOUSE | 27402 | 89 | 3-hydroxyacyl-CoA dehydrogenase type-2 |
| 9310 | 0.24 | 1112 \pm 165 | 272 \pm 222 | N.I. | | | | |
| 9402 | 0.20 | 607 \pm 30 | 123 \pm 153 | N.I. | | | | |

Searches were performed in the Swiss-Prot mouse database. In case no protein hits were obtained a subsequent search was performed in all Swiss-Prot databases. These hits are indicated with **

*, N.I.: not identified.

doi: 10.1371/journal.pone.0080600.t002

GalT-KO pig tissues. It is also reported that xenotransplantation may result in formation of antibodies directed towards a series of stress response and inflammation related proteins [20]. To evaluate whether knockout of the α 1,3-galactosyltransferase gene affects the expression of other proteins, we used a proteomic approach to analyze two different organs, liver and pancreas from wt as well as KO mice. These organs vary with respect to the expression of the α -Gal epitope, as it is present on the endothelial cells in the liver while absent on the endothelial cells in the pancreas. Indeed, we found several proteins as well as fragments in both organs with changed expression levels. Thus, it seems that protein turnover for some proteins is greatly influenced in the KO mice. The reason for these changes is unknown at present. Only few of the identified proteins contain N-glycosylation sites so it is unlikely that the presence or absence of the α -Gal epitope per se do play any role in the expression changes seen of proteins as well as their fragments.

Conclusion

We have analysed two different tissues of α 1,3-galactosyltransferase KO mice and revealed that deletion of

this gene that directly affects the expression of the α -Gal epitope affects a number of proteins with a wide variety of functions. Thus, it seems that protein turnover, i.e., synthesis and/or degradation, for some proteins is greatly influenced in tissues of the KO mice.

Acknowledgements

The authors are grateful for the excellent technical assistance provided by Inge Kjærgaard and Mona Britt Hansen.

Author Contributions

Conceived and designed the experiments: SK HV. Performed the experiments: LTU ML SK BH. Analyzed the data: LTU ML SK HV BH. Contributed reagents/materials/analysis tools: SK HV BH. Wrote the manuscript: LTU SK HV BH.

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